1/*f* noise in single-walled carbon nanotube devices

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We report the scaling behavior of $1/f$ noise in single-walled carbon nanotube devices. In this study we use two-dimensional carbon nanotube networks to explore the geometric scaling of $1/f$ noise and find that for devices of a given resistance the noise scales inversely with device size. We have established an empirical formula that describes this behavior over a wide range of device parameters that can be used to assess the noise characteristics of carbon nanotube-based electronic devices and sensors. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1812838]

Semiconducting single-walled carbon nanotubes (SWNTs) possess a number of unique properties including a high carrier mobility[1,2] and a high sensitivity to certain molecular adsorbates.[3] Motivated by these properties, researchers are exploring the use of SWNTs in a wide range of electronic applications including nanometer-scale devices,[4] microscopic thin-film transistors,[5,6] field-emission sources,[7] and chemical[8,9] and biological[10,11] sensors.

A less desirable property of carbon nanotube-based electronic devices is that they exhibit a large component of $1/f$ noise. Collins *et al.*[12] have shown that a wide variety of single- and multiwalled carbon nanotube devices, including individual SWNTs, two-dimensional networks, and three-dimensional mats of nanotubes, all exhibit a large value of $1/f$ noise that is proportional to the device resistance. This large value of $1/f$ noise is not surprising given that the electrical current in nanotubes is transmitted through surface atoms and is easily perturbed by local charge fluctuations. Because the magnitude of this noise is orders of magnitude larger than the noise observed in more conventional electronic materials,[12] $1/f$ noise is an important consideration in assessing the potential of carbon nanotubes for electronic and sensor applications.

In our laboratory we have studied electronic devices and chemical sensors consisting of two-dimensional networks of SWNTs.[5,8] These SWNT networks form an electrically continuous "fabric" of SWNTs that maintain the interesting electronic and sensor properties of individual SWNTs, while allowing us to construct devices of arbitrary size using conventional microfabrication technology. In the course of this work we have studied devices with a wide range of device dimensions and find that devices with similar resistances but with different sizes exhibit a systematic variation in the magnitude of $1/f$ noise. In particular, we observe that the level of $1/f$ noise in large-area devices is significantly less than the level of noise in small-area devices of comparable resistance. We have performed a systematic study of this behavior and have found an empirical formula that describes the $1/f$ noise over a wide range of resistance values and device dimensions. This result is a useful tool in assessing the noise characteristics of SWNT devices and indicates that for low-noise applications such as sensing, the use of large-area devices can significantly reduce the level of $1/f$ noise. We also find that the application of a gate bias increases the $1/f$ noise, with the level of noise increasing as a power law of the device off-state resistance.

The devices in the present study consist of electrically continuous two-dimensional networks of SWNTs. The SWNTs were either grown directly on the thermal oxide (200 nm thick) of a Si substrate using chemical vapor deposition or deposited onto the substrate from an aqueous 1% sodium dodecyl sulfate solution of suspended SWNTs. The deposited SWNTs were purchased from Carbon Nanotechnologies Incorporated. Titanium electrodes were deposited onto the SWNTs and patterned using metal liftoff. The regions between the electrodes were protected by photoresist and the unprotected regions of the SWNT network were removed using a CO_2 snowjet. The conducting Si substrate was used as common back gate. The width of the electrodes (W) and their spacing (L) was varied from 3 μm to 1 cm with aspect ratios (L/W) ranging from 1 to 0.02. The resistance of low-resistivity networks scales as L/W; however, the higher resistivity films display nonlinear scaling.[5] The low-frequency noise in these devices was measured using a Stanford Research Systems model SR830 lock-in amplifier and a Hewlett Packard model 3582A spectrum analyzer. The devices were either current or voltage biased; however, the results are reported as voltage power fluctuations per Hz, $S_V = \langle \Delta V^2 \rangle$, with $S_V = S_I R^2$, where R is the device resistance.

Collins *et al.* established that at low frequencies, carbon nanotube devices are dominated by a large component of $1/f$ noise.[12] Similar to other electronic systems, the magnitude of this $1/f$ noise is proportional to the square of the applied bias. By studying samples composed of a variety of different nanotubes ranging from individual SWNTs to felt-like mats of multiwalled carbon nanotubes, they found an empirical expression that describes the voltage noise density, given by

$$S_V = A \frac{V^2}{f^\beta}. \tag{1}$$

where the exponent β ranges between 1 and 1.1, and the prefactor A is equal to 10^{-11} R. This proportionality to R holds for resistance values spanning at least six orders of magnitude. The authors also note that this magnitude of $1/f$ noise is very large compared to the value found in more conventional electronic systems.

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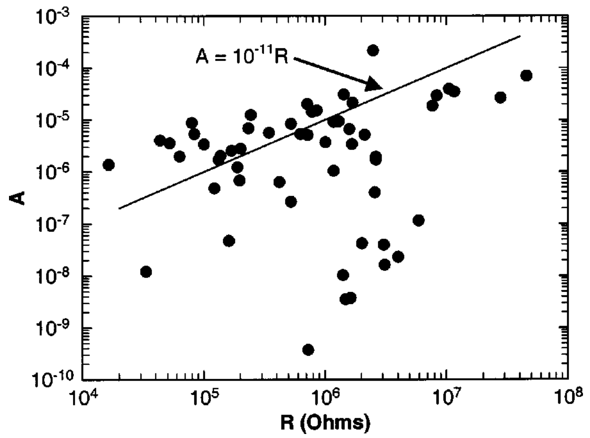

FIG. 1. Plot of the scaled noise, $A=fS_V/V^2$, measured in our two-dimensional networks versus the device resistance. The solid line corresponds to the empirical relationship established in Ref. 12.

In our two-dimensional network devices, which consist of a large number of intersecting SWNTs, we have confirmed the V^2/f scaling of the low-frequency noise. This behavior contrasts the scaling observed between two crossed multi-walled carbon nanotubes that deviate significantly from the V^2/f behavior.[13] Using the $f=10$ Hz noise in our devices[14] we take the approach of Collins *et al.* and plot the scaled noise, $A=fS_V/V^2$, versus device resistance (see Fig. 1). The solid line in the figure is a plot of $A=10^{-11}$ R. While there is a general agreement between the level of noise in our devices and the noise levels observed by Collins *et al.*, the data indicate that the resistance value alone is insufficient to predict the level of $1/f$ noise.

The reason that the $1/f$ noise magnitude in our devices does not correlate well with the resistance is that the devices were constructed using a wide range of sizes, and we find that the device size is an important additional component in predicting the magnitude of $1/f$ noise. In order to observe this size dependence we plot this same data set as A/R versus the electrode spacing L (see Fig. 2). By plotting the data as A/R we remove the resistance scaling observed by Collins *et al.*, and in this form the additional size dependence is clearly revealed. The horizontal dashed line in the figure represents the expression, $A/R=10^{-11}$, and for small device dimensions the noise levels that we observe are consistent with this

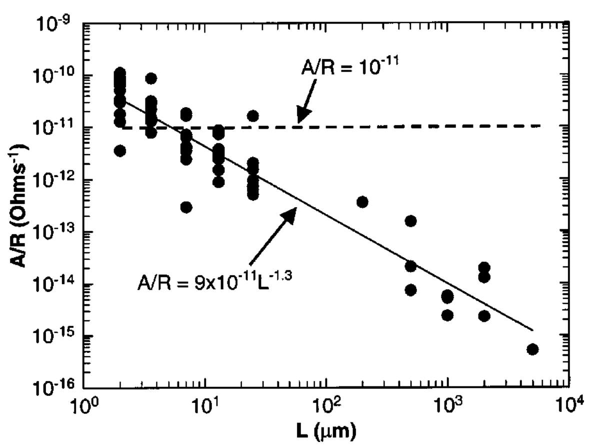

FIG. 2. The same data as in Fig. 1 plotted as A/R versus the electrode spacing L. The dashed line represents $A/R=10^{-11}$ (Ref. 12) and the solid line is a least-squares power-law fit to the data. A clear relationship between the level of $1/f$ noise and the device size is established.

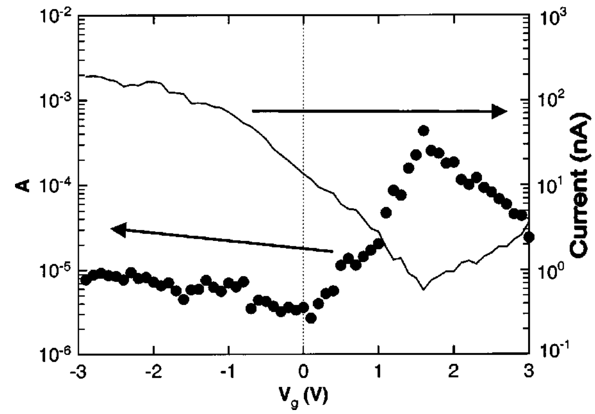

FIG. 3. The scaled noise (circles) and the drain current (line) for a typical device plotted versus the gate bias applied to the Si substrate. The noise has a minimum near $V_g=0$ and rises rapidly for positive gate biases. The noise peaks at the bias point ($V_g=1.6$ V), at which the network inverts to n-type conduction.

value. Although there is significant scatter in the data (which is expected given a random distribution of noise sources in a small sample volume) the trend is clear. The $1/f$ noise decreases systematically for larger devices; that is, for a network of a given resistivity, increasing the area of the device reduces the level of $1/f$ noise.

A least-squares power-law fit of the data (solid line) yields $A/R=9\times10^{-11}/L^{1.3}$, where L is in units of μm. The resulting empirical formula

$$S_V = 9\times10^{-11}\frac{R}{L^{1.3}}\frac{V^2}{f} \tag{2}$$

is a good predictor of the low-frequency noise in SWNT networks ranging in resistance from 10^4 to 10^7 Ω and spanning device areas from 10 to 10^8 μm^2. From this formula it is clear that for low-noise applications such as sensing that large-area SWNT devices will produce superior noise performance to nanometer-scale sensors. For comparison, this expression predicts that a 1-mm-sized, 1 MΩ SWNT sensor biased at 10 nA will exhibit $1/f$ noise in excess of the background thermal noise ($S_V=4kTR$) for $f<70$ Hz.

The reduction of the $1/f$ noise with device size is consistent with other electronic systems in which the magnitude of the $1/f$ noise varies inversely with the number of charge carriers (N) in the device.[15] According to this behavior the $1/f$ noise should scale as R/L^2 (i.e., $R/L^2=1/eN\mu$). The deviation from $1/L^2$ behavior that we observe is likely caused by the nonuniformity of the two-dimensional SWNT networks.

The R/L^2 behavior assumes a uniform system of uncorrelated noise sources that number in proportion to N. In contrast, the SWNT network consists of many parallel one-dimensional paths formed by intersecting SWNTs. The SWNTs consist of a mixture of both metallic and semiconducting nanotubes that have large variations in resistance, which results in nonuniform voltage drops along the conduction paths. Thus, the dominant noise sources will occur at the high-resistance segments of the current paths. We suppose that these nonuniformities are a significant contributing factor to the nonideal scaling behavior.

Another common characteristic of our devices is that the magnitude of the $1/f$ noise increases with the application of a gate bias V_g. Figure 3 plots the noise (and device current)

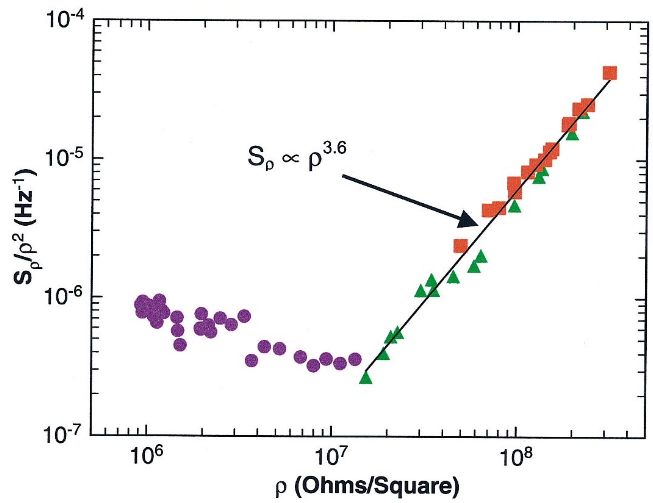

FIG. 4. (Color) The data in Fig. 3 plotted as the resistivity fluctuations versus the device resistivity. The circles correspond to $V_g<0$ V, the triangles to $0\ \mathrm{V}<V_g<1.6$ V, and the squares to $V_g>1.6$ V. As the gate bias shuts off the current in the network, the noise increases as a power law of the resistance. This behavior is similar to the $1/f$ noise scaling observed in percolating systems.

versus gate bias measured in a typical device. Note that the noise achieves its minimum value around 0 V and that the level of noise increases for both hole accumulation (negative gate bias) and depletion (positive gate bias) in the SWNT network. For positive gate bias the noise increases rapidly before peaking at $V_g=1.6$ V. This bias point corresponds to the bias at which the off-state current achieves a minimum indicating that the gate bias has inverted the network to n-type conduction.[16]

The source of gate-induced noise is not understood, but we note that field-induced charge fluctuations in the gate oxide is one possible cause. Because of their small diameter, the application of a gate bias creates a high electric field in the gate dielectric in the immediate vicinity of the SWNTs. At high gate biases this field is observed to cause significant charging of the gate dielectric that manifests itself as a hysteresis in gate bias sweeps.[17] Therefore, the gate field might also produce charge fluctuations in the SiO_2 gate dielectric that increases the level of $1/f$ noise. The role of the substrate in $1/f$ noise has been noted by other researchers, who have observed a significant reduction in the level of $1/f$ noise in transport measurements on nanotubes that are suspended above the substrate.[18]

For positive gate bias, the noise increases rapidly and peaks at the point at which the networks inverts from p-type to n-type conduction. To further elucidate this behavior, we plot in Fig. 4 the normalized resistivity fluctuations S_ρ/ρ^2 $(=S_V/V^2)$ versus resistivity (ρ) for this same device. The data are divided into three sets: $V_g<0$ (circles), $0\ \mathrm{V}<V_g<1.6$ V (triangles), and $1.6\ \mathrm{V}<V_g<3$ V (squares). As seen in the figure, all of the data for $V_g>0$ exhibit a power-law scaling versus resistivity. This scaling is observed for gate biases both above and below the inversion point at $V_g=1.6$ V. A least-squares power-law fit to the data (solid line) results in $S_\rho \propto \rho^{3.6}$. Such a power-law behavior is characteristic of the $1/f$ noise in percolating systems in which $S_\rho \propto \rho^q$, with q ranging between 2.7 and 6.[19,20] In such systems, near the percolation threshold the conduction paths are highly nonuniform making them more susceptible to fluctuations that lead to a large increase in noise.

This similarity to the behavior observed in percolating systems is not surprising given the structure of the SWNT network that in many ways resembles a random resistor network near the percolation threshold.[21] For $0\ \mathrm{V}<V_g<1.6$ V, the gate bias shuts off the hole conductivity in the semiconducting nanotubes causing the network resistance to rapidly increase. This process is analogous to the random removal of resistors from a resistor network near the percolation threshold. For $V_g>1.6$ V, the conductivity is restored by inverting the nanotubes to n-type conductivity, in effect reversing the process. Remarkably, we observe that the power-law behavior of the noise is nearly identical on either side of the inversion point.

In summary, we have investigated the behavior of $1/f$ noise in two-dimensional networks of SWNTs. We have found an empirical expression [Eq. (2)] that predicts the noise in SWNT networks that range in size from 10 to 10^8 μm^2 and span resistance values from 10^4 to 10^7 Ω. This expression is a useful tool in assessing the noise characteristics of SWNT devices, and for low-noise applications such as sensing increasing the size of the device can significantly reduce the level of $1/f$ noise. We also find that the application of a gate bias increases the noise in SWNT devices with the noise increasing as a power law of the device off-state resistance. This power-law scaling is similar to the scaling of $1/f$ noise in percolating systems approaching the percolation threshold.

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